

# Epitaxial Co/NiAl Thin Film Growth on Si Substrates

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## ABSTRACT

Quad-crystal Co/NiAl/Ag thin films were epitaxially grown on hydrofluoric acid etched Si(111) single crystal substrates by sputter deposition. The orientation relationship was studied by x-ray  $\theta/2\theta$  diffraction and pole figure  $\phi$ -scan, and it was determined to be  $\text{Co}(10\bar{1}1) \parallel \text{NiAl}(110) \parallel \text{Ag}(111) \parallel \text{Si}(111)$ . The Ag layer contains two twin-related orientations of grains. NiAl grows with three variants of grains on the Ag(111) layer. Since  $\text{Co}(10\bar{1}1)$  contains grains with four possible easy axis directions when grown on each NiAl variant, the quad-crystal media consist of grains with twelve easy axis directions and exhibit nearly isotropic in-plane magnetic properties. Meanwhile, uni-crystal  $\text{Co}(10\bar{1}0)/\text{NiAl}(112)$  films were also epitaxially grown on Ag(110)/HF-Si(110) templates. The orientation relationships determined from these epitaxial films were very useful in understanding the texture evolution of the Co alloys on NiAl. It indicates that the Co  $(10\bar{1}0)$  texture evolution on the  $(110)$  texture of NiAl on amorphous substrates, such as NiP/AlMg or glass, is due to a difficult to observe NiAl  $(112)$  texture on the top of the  $(110)$  texture.

## INTRODUCTION

Co-based alloys are currently the most popular thin film medium materials for magnetic recording. In order to achieve the optimal magnetic properties, control of the Co-alloy film texture is essential. Textures that induce in-plane Co easy axes are usually desired in order to obtain a high coercivity, and this is most often achieved by using Cr underlayers due to the lattice matching between Cr and Co. One of the most common lattice match relationships between Co and Cr for longitudinal recording is the quad-crystal structure, in which Co has four possible easy axis orientations on the Cr(110) lattice, and the Co easy axes are tilted  $28^\circ$  out of the film plane. Another lattice match relationship is the uni-crystal structure for which only one Co easy axis orientation is observed on the Cr(112) plane.

In order to investigate new underlayers while exploiting the unique properties of the Cr underlayer, NiAl intermetallic with B2 ordered crystal structure (space group  $\text{Pm}\bar{3}\text{m}$ , CsCl

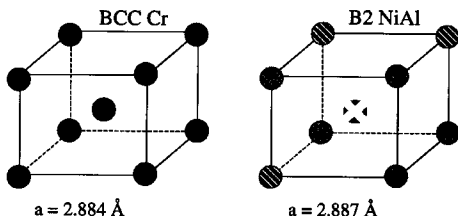


Fig. 1. Lattice structures of BCC Cr and B2 NiAl.

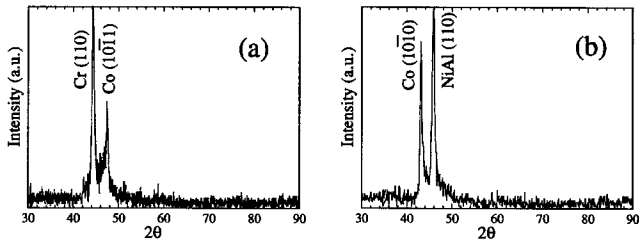


Fig. 2. X-ray diffraction spectra of (a) a Co(50nm)/Cr(100nm) film, and (b) a Co(50nm)/NiAl(100nm) film, both samples were deposited at room temperature.

prototype) was successfully developed as an alternative underlayer material for low noise Co-alloy recording media [1]. Fig. 1 compares the very close lattice spacing values and similar unit cell structures of Cr and NiAl. The similarities would lead one to anticipate the same Co texture evolution on NiAl as on Cr. Moreover, compared with the widely used Cr underlayers, NiAl thin films exhibit smaller and more uniform grains, which in turn induces smaller grains in the Co alloy films resulting in an improved media signal to noise ratio [2]. It was reported that a NiAl underlayer was adopted in the media structure of IBM's 10 Gbit/in<sup>2</sup> magnetic recording demonstration [3].

Despite the similarity between Cr and NiAl, NiAl underlayers seem to show some distinct characteristics during the texture evolution. Fig. 2 shows the x-ray diffraction patterns of a Co(50nm)/Cr(100nm) film [Fig. 2(a)] and a Co(50nm)/NiAl(100nm) film [Fig. 2(b)]. Both of the samples were sputter deposited on glass substrates at room temperature and the x-ray diffraction scans indicated that the Cr and NiAl grew with the (110) textures. However, the textures of the Co films on the Cr and NiAl underlayers are different. The Co film on the (110) textured Cr film was observed to develop a  $(10\bar{1}1)$  texture while that on the (110) textured NiAl developed a  $(10\bar{1}0)$  texture. It has been suggested that a difficult to observe (112) NiAl texture evolves on top of the (110) texture [4]. In order to investigate this apparent growth contradiction, epitaxially grown NiAl films with highly pure textures were needed. In this study, NiAl(110) and NiAl(112) films were epitaxially grown by sputter deposition using Ag/HF-Si templates. Then Co films were epitaxially grown on these highly pure textured NiAl films and the epitaxial relationships between the Co and NiAl were studied.

#### EPITAXIAL GROWTH OF NiAl

To grow highly oriented NiAl films, HF-etched Si wafers were used as substrates, and epitaxially grown Ag films were used as templates to induce the desired orientations in the NiAl. In particular, NiAl(110) films were grown on Ag/HF-Si(111) to investigate the Co texture evolution on pure (110) textured NiAl underlayers. As we reported earlier, Ag grows epitaxially on Si(111) with a (111) orientation [5]. The NiAl layer then grows with three variants of grains on the Ag(111) layer, with the following orientation relationships:

$$\text{NiAl}(110)[001] \parallel \text{Ag}(111)[1\bar{1}0] \parallel \text{Si}(111)[1\bar{1}0],$$

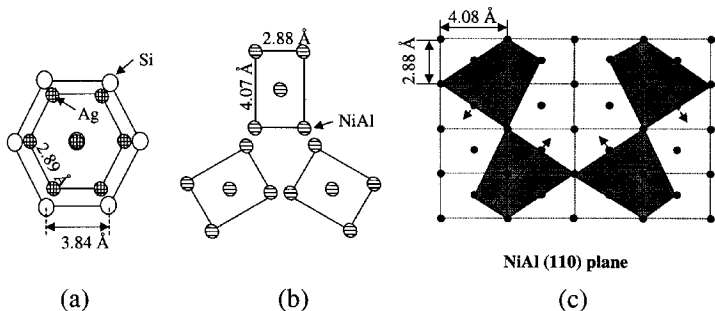


Fig. 3. Orientation and interatomic spacing relationships (a) between Si(111), Ag(111), and (b) NiAl(110) lattices. Note the three possible orientations of NiAl(110) on Ag(111). (c) Lattice match relationship between Co(10 $\bar{1}$ 1) and NiAl(110) planes.

$$\begin{aligned} \text{NiAl(110)[001]} &\parallel \text{Ag(111)[10}\bar{1}] \parallel \text{Si(111)[10}\bar{1}], \\ \text{NiAl(110)[001]} &\parallel \text{Ag(111)[01}\bar{1}] \parallel \text{Si(111)[01}\bar{1}]. \end{aligned}$$

The epitaxial orientation relationships for the quad-crystal Co/NiAl/Ag/HF-Si(111) films are shown in Fig. 3. The Co layer contains grains with four possible easy axis directions when grown on each NiAl variant. As a result, the grains in the quad-crystal media can take on one of twelve possible easy axis directions.

#### EXPERIMENTAL DETAILS

Si(111) wafers were first ultrasonically cleaned in organic solvents and rinsed in deionized water. The clean wafers were then immersed in HF to remove the native SiO<sub>2</sub> and obtain a hydrogen-terminated surface. The etched wafers were blown dry using N<sub>2</sub> gas, then placed into the sputtering system, and heated to about 200°C in vacuum before deposition. Ag, NiAl, and

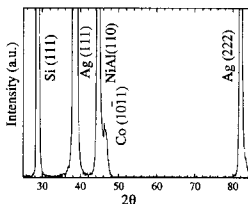


Fig. 4 X-ray diffraction patterns of a quad-crystal Co(30nm)/NiAl(50nm)/Ag(75nm) film on HF-Si(111).

Co thin films were then deposited by rf diode sputtering in a Leybold-Heraeus Z-400 sputtering system. The base pressure was below  $5 \times 10^{-7}$  Torr. The Ar sputtering gas pressure was fixed at 10 mTorr and the sputtering power density was about 2.3 W/cm<sup>2</sup>. The epitaxial structure of the films was studied by x-ray  $\theta/2\theta$  diffraction and pole figure  $\phi$ -scan.

## RESULTS AND DISCUSSION

### Quad-Crystal Co/NiAl Films

The  $\theta/2\theta$  x-ray diffraction spectrum for a Co(30nm)/NiAl(50nm)/Ag(75nm) film grown on HF-Si(111) is shown in Fig. 4. Only Ag(111), Ag(222), NiAl(110) and Co(10 $\bar{1}$ 1) diffraction peaks are observed. These very strong diffraction peaks, as compared to the background noise level, imply the epitaxial nature of the film.

The  $\phi$ -scan spectra of the Co/NiAl/Ag/HF-Si(111) sample are shown in Fig. 5, along with Si(111), Ag(111), NiAl(110), and Co(10 $\bar{1}$ 1) stereographic projections that are necessary for the interpretation of the spectra. As can be seen in Fig. 5(a), the Si{220}-pole scan spectrum of the single crystal Si(111) substrate shows three diffraction peaks with 120° separation. They correspond to the three {110} poles in the Si(111) stereographic projection [Fig. 5(a')], which are also 120° apart along the dotted circle showing the  $\phi$ -scan path.

While three Ag{110} poles are expected for single crystal Ag(111), six peaks were observed in the Ag{220}-pole scan [Fig. 5(b)] of the Ag(111) film grown on Si(111). This suggests that there exist two twin-related orientations of Ag grains in the Ag(111) film. They may emerge at the Ag/Si epitaxial interface or result from Ag growth twinning. In fcc metals, the (111) plane is the most common twinning plane, and the twinning direction is  $[11\bar{2}]$ . The extra poles are indicated by the "x" symbol in Fig. 5(b'). Three of the peaks, the first, third and fifth, appear at the same  $\phi$  positions as the three peaks in Si{220}-pole spectrum, confirming the parallel relationship between the Si[1 $\bar{1}$ 0] and Ag[1 $\bar{1}$ 0] directions. The twinning was also confirmed by electron diffraction patterns [5].

Similarly, while two NiAl{001} poles are anticipated for single crystal NiAl(110), the NiAl{002}-pole scan spectrum [Fig. 5(c)] shows six peaks that are 60° apart. They appear at the same locations as the six peaks in the Ag{220}-pole scan. This confirms not only the three possible growth variants of NiAl grains on Ag(111), but also that the three NiAl{001} directions are parallel to the three Ag[1 $\bar{1}$ 0] directions. The two extra sets of poles are denoted by "x" and "+" in the stereographic projection in Fig. 5(c').

Finally, with four possible orientations of Co grains on each NiAl variant, as indicated by the four (10 $\bar{1}$ 0) poles (marked  $a_1$  to  $a_4$ ) or the four (0001) poles (marked  $c_1$  to  $c_4$ , as these are also the easy axis directions), there will be altogether twelve (10 $\bar{1}$ 0) poles. The two extra sets of poles are denoted by "x" and "+". As shown in Fig. 5(d'), the twelve poles can be divided into six groups, inside each group there is a separation of about 10° along the  $\phi$ -scan path, while the neighboring two groups are 60° away from each other. The observed Co(10 $\bar{1}$ 0)-pole scan [Fig. 5(d)] agrees well with the projection. Also as expected, each two-peak group is centered about the six NiAl peaks in the NiAl{002}-pole scan spectrum.

### Uni-Crystal Co/NiAl Films

Previously, Yang et al. [6] reported the epitaxial growth of the uni-crystal Co(10 $\bar{1}$ 0)/Cr(112) films on Ag(110)/HF-Si(110). Using the same technique, uni-crystal Co/NiAl films were grown on sputter deposited Ag(110)/HF-Si(110). Fig. 6 shows the x-ray diffraction pattern of a uni-crystal film, which can be compared to the quad-crystal pattern of Fig. 4. Only the NiAl(112) and Co(10 $\bar{1}$ 0) peaks are observed. With the x-ray pole figure  $\phi$ -scan spectra, the epitaxial

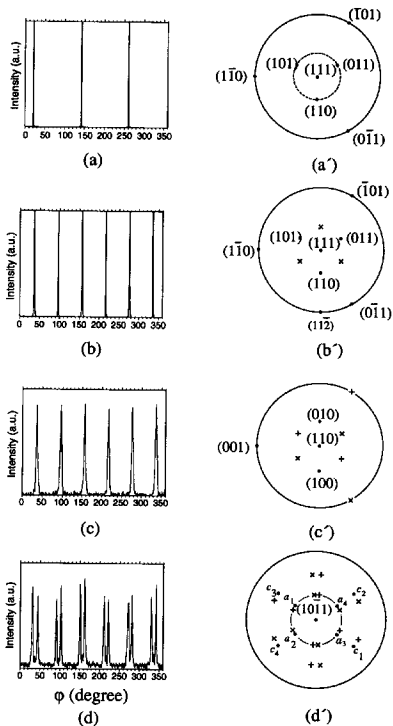


Fig. 5 (a) Si{220}-pole, (b) Ag{220}-pole, (c) NiAl{002}-pole, and (d) Co(10 $\bar{1}$ 0)-pole  $\phi$ -scan spectra of a Co(30nm)/NiAl(50nm)/Ag(75nm)/HF-Si(111) film. The stereographic projections are for (a') Si(111), (b') Ag(111), (c') NiAl(110), and (d') Co(10 $\bar{1}$ 1).

relationships were determined to be the same as those of Co(10 $\bar{1}$ 0)/Cr(112)/Ag(110)/HF-Si(110) [6].

### Co Texture Evolution

With the epitaxial NiAl underlayers which show highly pure textures, it is determined that the NiAl(110) plane only induces Co(10 $\bar{1}$ 1), while the NiAl(112) only induces Co(10 $\bar{1}$ 0).

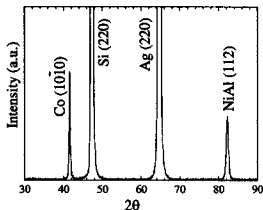


Fig. 6 X-ray diffraction patterns of a uni-crystal Co(30nm)/NiAl(50nm)/Ag(75nm) film on HF-Si(110).

Hence, the  $(10\bar{1}0)$  Co texture on the  $(110)$  textured NiAl underlayers grown on amorphous substrates can not be a result of the epitaxial growth of Co $(10\bar{1}0)$  on the NiAl $(110)$ . The only possibility is that on top of the  $(110)$  textured NiAl films, a  $(112)$  texture has developed and induced the  $(10\bar{1}0)$  Co texture. Since the  $(112)$  texture develops late, it was difficult for the x-ray diffraction to detect the relatively low  $(112)$  peak intensity at the high  $2\theta$  angle.

## CONCLUSIONS

In this work, we have successfully fabricated quad-crystal Co thin-film media on NiAl  $(110)$ /Ag $(111)$ /HF-Si $(111)$  by sputter deposition. The epitaxial orientation relationship was determined by x-ray pole figure scan. Two twin-related orientations were found in the Ag $(111)$  layer. NiAl grows with three possible variants on Ag $(111)$  and this finally results in twelve easy axis directions in the Co $(10\bar{1}1)$  layer. Also the uni-crystal Co $(10\bar{1}0)$  films were grown on NiAl $(112)$ /Ag $(110)$ /HF-Si $(110)$ . Using these NiAl films with highly pure  $(110)$  and  $(112)$  orientations, the texture evolution of Co on NiAl underlayers was examined.

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